

## Synthesis, Structure, and Magnetic Properties of an $\text{Al}_2\text{O}_3/\text{Ge-p}/\text{Al}_2\text{O}_3/\text{Co}$ Thin-Film System

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**Abstract**—Structural and magnetic measurements are made of an  $\text{Al}_2\text{O}_3/\text{Ge-p}/\text{Al}_2\text{O}_3/\text{Co}$  thin-film system. The structure is synthesized via ion-plasma deposition and can be used as a tunnel heterostructure. The dependences of the magnetic properties of cobalt on the rate of its deposition and the rates of deposition of preceding layers are established.

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### INTRODUCTION

The importance of studying the mechanisms responsible for the physical properties of ferromagnetic metal/dielectric/semiconductor thin-film structures remains relevant today. To ensure the desired properties when synthesizing such structures, we must solve the difficult problem of forming high-quality interfaces between layers. It is therefore vital to examine the effect interfaces between layers have on the formation of a structure, its physical properties (magnetic and otherwise), and thus its spin-dependent transport [1–3]. In this work, we chose samples of  $\text{Al}_2\text{O}_3/\text{Ge-p}/\text{Al}_2\text{O}_3/\text{Co}$  as our objects of study.

### EXPERIMENTAL

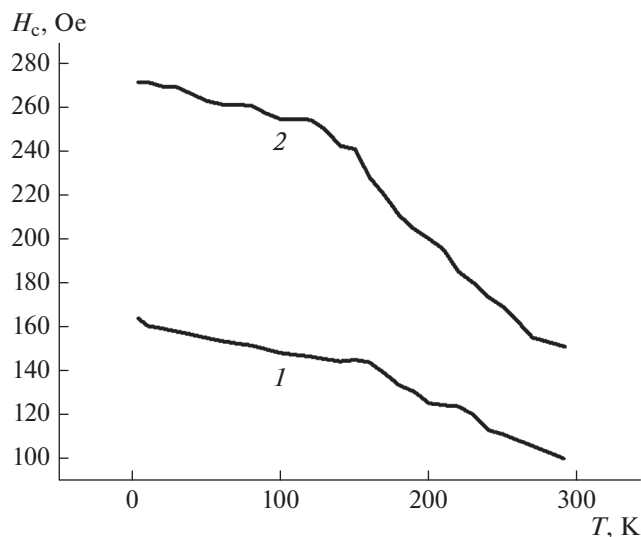
$\text{Al}_2\text{O}_3/\text{Ge-p}/\text{Al}_2\text{O}_3/\text{Co}$  structures were obtained via ion-plasma deposition at a base pressure of  $p = 10^{-6}$  Torr in an argon atmosphere. The substrate material was Si(001), preliminarily cleaned by ion-plasma etching in a working chamber prior to deposition. We synthesized two series of film samples deposited at different rates. The rates of  $\text{Al}_2\text{O}_3$  deposition differed by an order of magnitude; those of Ge-p and Co deposition, by a factor of 5. In addition, we formed pure cobalt films at the same rates of deposition on identical substrates preliminarily cleaned by ion-plasma etching. The films of the first type were (i)  $\text{Al}_2\text{O}_3$  (0.5 Å/min/33 nm)/Ge-p (24 Å/min/54 nm)/ $\text{Al}_2\text{O}_3$  (0.5 Å/min/4.7 nm)/Co (12 Å/min/104.7 nm) and (ii) Co (12 Å/min/1000 Å). The films of type 2 were (i)  $\text{Al}_2\text{O}_3$  (5.5 Å/min/220 nm)/Ge-p (144 Å/min/31 nm)/ $\text{Al}_2\text{O}_3$  (5.5 Å/min/16 nm)/Co (72 Å/min/106 nm) and (ii) Co (72 Å/min/1000 Å).

Cross-sectional TEM images of the structures were obtained on a Hitachi HT7700 transmission electron microscope. The surface structure of the films was examined on a Veeco Multi Mode atomic force microscope. Magnetism was measured using a NanoMOKE-2 magneto-optical Kerr effect setup and a Quantum Design MPMS\_XL SQUID magnetometer.

According to the cross-sectional TEM images of the structures, ion-plasma etching produced smooth, continuous interfaces between the substrates and  $\text{Al}_2\text{O}_3$  layers with a roughness of around 1–2 nm in both types of films. In the first type of films, however, the roughness of the interfaces between the subsequent layers changed weakly. In the second type of films, it changed more abruptly.

We determined the roughness parameters for the upper cobalt layer in each pure cobalt sample and the  $\text{Al}_2\text{O}_3/\text{Ge-p}/\text{Al}_2\text{O}_3/\text{Co}$  multilayers using atomic force microscopy. Analysis showed that the roughness of the pure cobalt film was halved as the rate of deposition of the latter slowed. In the  $\text{Al}_2\text{O}_3/\text{Ge-p}/\text{Al}_2\text{O}_3/\text{Co}$  multilayers, it fell by a factor of 3–5 with as the rate of deposition of each subsequent layer slowed. Cobalt roughness  $R_a$  in the first type of samples ( $\text{Al}_2\text{O}_3/\text{Ge-p}/\text{Al}_2\text{O}_3/\text{Co}$ ) fell to 3–4 Å in particular. The rate of deposition of the intermediate layers thus affected the roughness of the upper layer.

Our magnetic measurements showed that the room-temperature coercivity of the  $\text{Al}_2\text{O}_3/\text{Ge-p}/\text{Al}_2\text{O}_3/\text{Co}$  structures was significantly higher than that of the pure cobalt films.



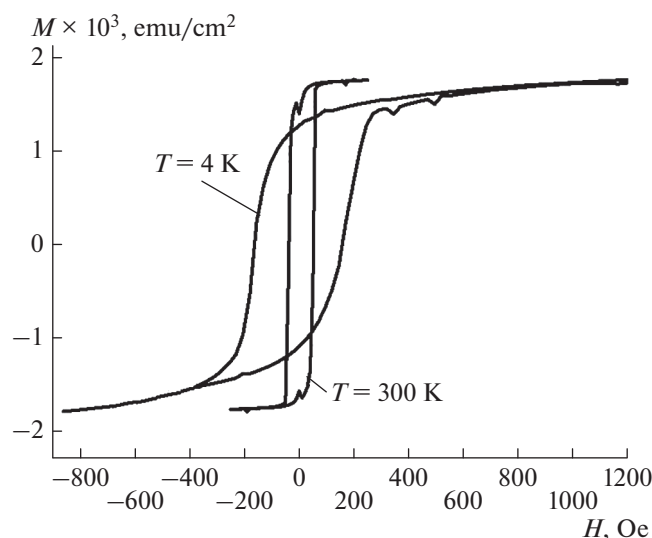
**Fig. 1.** Temperature dependence of coercivity for the  $\text{Al}_2\text{O}_3/\text{Ge-p}/\text{Al}_2\text{O}_3/\text{Co}$  samples deposited at the first (slow) and second (high) types of rates.

$\text{p}/\text{Al}_2\text{O}_3/\text{Co}$  system at low rates of deposition (the first type) was 100 Oe; as the temperature fell to 4 K, it grew to 160 Oe. At high rates of deposition (the second type), the room-temperature coercivity was  $\sim 160$  Oe; as the temperature fell to 4 K, it grew to 280 Oe. At the same rate of deposition of pure cobalt and cobalt in the  $\text{Al}_2\text{O}_3/\text{Ge-p}/\text{Al}_2\text{O}_3/\text{Co}$  system (curve 1 in Figs. 1 and 2), its coercivity differed by a factor of two or more, depending on temperature. It is well known [4] that the fraction of the hexagonal phase falls along with the rate of cobalt deposition and additional phases arise. The difference between the coercivities of the samples and the steepness of their temperature dependences could thus be associated with the rate of deposition of cobalt underlayers in the system, since the surface relief depends on the rate of deposition of the preceding layer and thus affects the structure of the next layers. We may therefore conclude that the change in the coercivity in the  $\text{Al}_2\text{O}_3/\text{Ge-p}/\text{Al}_2\text{O}_3/\text{Co}$  systems was due to anisotropy at the interface.

### CONCLUSIONS

Our study of the  $\text{Al}_2\text{O}_3/\text{Ge-p}/\text{Al}_2\text{O}_3/\text{Co}$  system revealed the dependence of the magnetic properties of cobalt on the rate of its ion-plasma deposition and those of the deposition of the layers preceding this cobalt layer. By slowing the rate of layer deposition in a multilayer structure, we can reduce the roughness of the interfaces between adjacent layers and the average grain size, thereby lowering and stabilizing coercivity.

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**Fig. 2.** Hysteresis loops for the pure cobalt layer at  $T = 300$  and 4 K in the first (slow rate) type of rates.

This can be used in designing spintronic devices, including magnetic sensors.

To describe the magnetic anisotropy in ferromagnetic metal/semiconductor systems in more detail, we must consider actual electronic and interfacial structures [5], since interfaces are only a few nanometers thick and new phases can form in them.

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